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Feasibility of significant CO_2 emission reductions in thermal power plants – comparison of biomass and CCS

Antti Arasto[a]*, Eemeli Tsupari[a], Janne Kärki[a], Risto Sormunen[b], Timo Korpinen[b], Sari Hujanen[b]

[a]VTT Technical Research Centre of Finland, Biologinkuja 5, 02044, Espoo, Finland
[b]Fortum Power & Heat Oy, Keilaniemi, 00048 Espoo, Finland

Abstract

In the future greenhouse gas emission targets will be more ambitious and therefore solutions for of CO_2 emissions reduction more than 80% are sought. In thermal power plants these high levels of emission reductions can be reached with CCS technologies or by utilizing high shares of biomass based fuels. Following from the national targets of Finland, the power plants being planned at the moment need to take these targets into account in the planning phase as options that need to be fulfilled at least in the future if not immediately. In this paper high plant level CO_2 emission reduction targets are analysed for two large power plants that are planned to be constructed in Finland in the near future. Both are located close to urban areas and supply also district heat to neighboring cities. Both also face high political pressure to significant emission reductions in comparison to existing system.

This paper is based on a case study of a planned combined heat and power (CHP) plant in Finland having fuel power of $420MW_{fuel}$. The boiler island is plant based on circulating fluidized bed (CFB) boiler technology enabling combustion of high shares of biomass. The paper is shortly describing technologies that are needed for reduction of CO_2 emissions when carbon capture based on oxyfuel technology and biomass firing based on high shares of forest residues are considered. The implications of applying these technologies and suitability for CHP environment are considered and economic feasibility of the solutions compared. Also the possibilities and feasibility of reaching negative emissions with combination of biomass firing and CCS is briefly assessed.

Results show significant emission reduction potential associated to both technologies. The major costs associated to CCS are caused by the equipment investment, loss of electricity production due to energy penalty and transportation and storage of CO_2. The costs associated to biomass combustion with high shares are mainly caused by higher prices of biomass fuel in comparison to coal and lower power-to-heat ratio. Large biomass share has an increasing impact also on plant investment and O&M costs.

* Corresponding author. Tel.: +358 400 159 052.
E-mail address: antti.arasto@vtt.fi

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On the other hand, significant savings are achieved in terms of CO_2 allowances. When discussing the biomass option one must also address questions related to availability of sustainable biomass, effecting pricing and competition of raw material between different uses such as forest industry or liquid biofuels production. And this further highlights the discussion on carbon stocks and carbon debt especially when Bio-CCS is considered.

If the profound emission reduction targets are to be met, economically the difference between the technologies considered is not clear in all circumstances. All the most important parameters for the economic lifetime of the power plant include significant uncertainty therefore in this paper main focus has been in sensitivity analysis. The study reveals some major economical restrictions of the applicability of these emission reduction solutions. The pros and cons of the technologies in the light of feasibility and the role of these technologies as carbon abatement tools are discussed. The major factor effecting the technology decision is plant location in relation to availability of biomass, coal and CO_2 transportation&storage options, as well as heat demand (possibility to utilize CHP) in addition to political atmosphere and acceptability of technologies.

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Keywords: Oxy-fuel; co-firing; Bio-CCS; BECCS; CHP, feasibility

1. Introduction

1.1. Greenhouse gas emission reduction targets

The urgency to stabilize the global temperature rise at 2°C calls for solutions that can remove CO_2 from the atmosphere. In the future greenhouse gas (GHG) emission targets will be more ambitious and therefore solutions for reduction of CO_2 emissions more than 80% are sought to reach the profound targets. Currently European Commission is proposing a uniform 40% GHG reduction targets for ETS (sectors within European Emission Trading Scheme, like energy and GHG intensive industry) and Non-ETS sectors (such as households, agriculture, transport) [1]. CCS (Carbon Capture and Storage) and bioenergy both seem to have a significant role in reaching the high emission reduction targets in Europe and also in Nordic countries [2].

In principal, there are two technical solutions to significantly reduce GHG emissions in thermal power plants: carbon capture and storage (CCS) technologies and fuel switch e.g. by utilizing high shares of biomass based fuels. Combining these two can also lead to a carbon sink [3]. The technical and economic feasibility of these GHG mitigation solutions are investigated in this paper through a case study on power plant situated in Finland. National taxes and renewable subsidies are not included in order to make the results widely applicable and to investigate the non-political (other than CO_2) feasibility order of these solutions.

1.2. Co-firing of biomass and technical applicability of CCS to biomass co-firing plant

Co-firing of coal and various kinds of biomasses is now a mature technology and is currently being practiced all over the world successfully, though it does not eliminate CO_2 emissions entirely. Fluidized bed boilers provide the best fuel flexibility for co-firing. With properly designed CFB boilers, biomass fuels can be co-fired with coal on 0–100 % share [4].

In general, similar solutions are suitable for capturing CO_2 from biomass applications as for fossil fuels. The main differences relate to different kind of impurities in the combustion process, ash and flue gas and typically significantly larger moisture content of biomass resulting more vapor in flue gases enabling also high heat recovery potential. However, no principal technical restrictions with the capture of biogenic CO_2 exist. Despite of fluidized bed technology's high flexibility regarding the fuels, in the case of biomass combustion some challenges exist. Some of these challenges may be emphasized in the case of utilization of CCS. For example with oxy-fired fluidized bed boilers even small concentrations of chlorine in the fuel can lead to deposits of harmful alkaline and chlorine compounds on boiler heat transfer surfaces due to components enrichment in the flue gas because of lack of nitrogen in furnace and flue gas re-circulation.

Co-firing seems to be a near-term solution for the moderate reductions of GHG emissions. It is the most efficient means of power generation from biomass, and it thus may offer CO_2 avoidance cost lower than that for CO_2 capture, provided the availability of reasonably priced carbon neutral biomass [5]. Both options are applicable for both, existing and new power plants. In this study feasibility of investments on significant GHG mitigation options for new plant are compared with the feasibility of reference case investment in different market situations.

2. Methodology

The basis for the techno-economic assessment is the modelling of process environment, and application of different CO_2 reduction technology options to the modelled environment. All modeling work was carried out using Fortum's Power Plant simulator Solvo™. Solvo™ is a product developed by Fortum and has been in use since 1991. Fortum Solvo™ is a versatile tool for the design and optimization of power plant processes for professional use. The calculation is based on balanced mass and energy flow of components, and on equation solutions representing the operation of the equipment.

Based on the energy and material balances obtained from the modelling and the technical feasibility of solution the economic profitability is evaluated. CO_2 emission reductions are estimated within the system boundary (i.e. from an investor's point of view, CO_2 accounted for operator in EU ETS). The idea of the economic assessment was to recognize the significant differences between the GHG mitigation options and the reference case from the economic point of view. Costs and heat utilization scenarios were investigated with a custom-built CC-Skynet™ economics toolkit based on costs of the whole chain, including fuel purchase, CO_2 capture, processing, transport and storage.

2.1. Reference case and operation environment

In Finland, the power plants being planned at the moment are mainly combined heat and power plants (CHP) and thus the size of the plants is significantly smaller than with condensing units. The smaller plant size and heat generation requirements need to be taken into account in the planning phase also when analyzing suitable CCS technology options for this type of plants. CHP production generally entails relatively low specific costs for electricity and earlier dispatch in merit order due to heat demand and income. The CHP connection also offers different operation optimization schemes due to heat production guarantee agreements and other potential CHP or heating plants in the heating network, owned by the same operator.

This paper is based on a case study of a CHP plant having fuel capacity of ca. 420MW_{fuel} in a CFB boiler technology designed to enable combustion of high shares of biomass. In comparison to conventional CFB plant design there are some technology and design changes that are needed for reduction of CO_2 emissions as the carbon capture of the case plant is based on oxy-fuel technology and biomass firing with high shares of forest residues. The reference case CHP plant would be the main generation unit in a district heating system where the case plant would cover ca. 35 - 40 % of the peak winter heat demand generating ca. 50 - 55 % of the annual district heat and steam energy consumption in the network (ca. 4 TWh/a). Basically CHP plant is operated according to the heat demand in the system and thus also the generated energy varies with the different process alternatives studied in the paper depending on the case specific optimization, different efficiencies in heat and electricity production etc. During summer time, because of the low heat demand in the system, energy is generated using other boilers due to the minimum load requirements of the main unit. The heat demand and production changes are displayed in Figure 1.

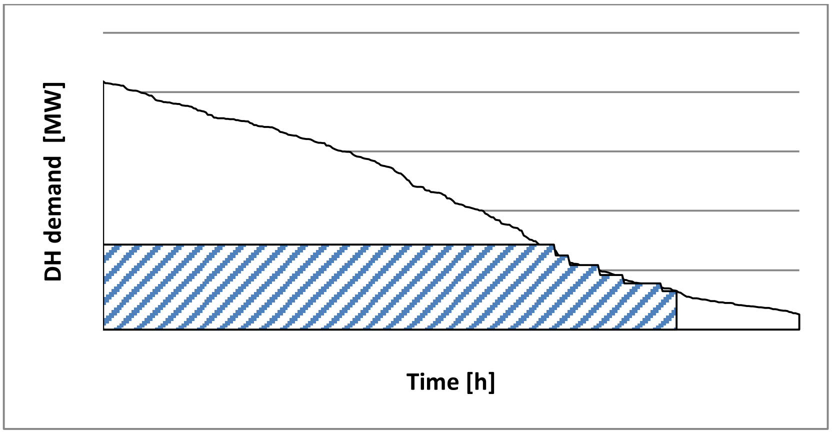

Figure 1. Annual district heat and steam demand and production of the studied CHP plant (lined area) at reference point without CCS (ca. 2100 GWh/a vs. total demand of 4000 GWh/a.

The planned CHP plant is producing at reference point ca. 280 MW of process steam and district heat, and ca. 125 MW electricity according to design criteria. Steam turbine is back pressure type turbine with extractions for the preheaters, process steam and district heat. The boiler part concept was matched to the latest design criteria of known boilers.

2.2. *Properties of oxy-CFB*

For CCS an oxygen-fired CFB boiler has been modelled so that the boiler is capable in operating both with air mode and oxy-fuel mode. In different case studies the boiler size i.e. fuel power was fixed for the same magnitude. The boiler was modeled as a simplified balance model according to DIN 1942 standard. The most variable parameters e.g. the flue gas temperature after the economizer and at the different parts of the flue gas path and in oxy-fuel cases the oxygen demand, oxygen/flue gas mixtures temperature and O_2-consistency (21 - 27 vol-% depending on the biomass share and boiler load) to the boiler were modeled.

In Oxy-fuel cases the recirculation gas is taken after the electrostatic precipitator. The amount of the circulating gas is adjusted based on the O_2-consitency in the O_2-flue gas mixture to the boiler. The oxygen is preheated up to 122°C with flue gases going to the CO_2 purification (CPU) unit and then mixed with recirculation gas after the air preheaters so that the total oxygen content after the mixing varied between ca. 21-27 vol-%. After mixing, the oxygen-flue gas mixture is supplied to the boiler as primary and secondary air. There should be no significant risk of ignition involved if proper mixing of oxygen to the recirculation flow is taken care of.

Before the CPU flue gas must be dried and cooled and thus a flue gas condenser is necessary. District heating water is being used as coolant in the flue gas condenser producing extra district heat. An extra sea water cooled flue gas condenser is added to dry the flue gas before the CPU.

Steam turbine selected for the scenarios of this study is a back pressure type turbine but also a condensing turbine option was analyzed for comparison. Live steam and reheat steam parameters are set to meet current CHP requirements in a process generating also steam for industrial purposes. Turbine is equipped with extractions to condensate and feed water preheaters, district heaters and process steam (20 bar and 5 bar) consumers. Steam turbine efficiencies are estimated based on the knowledge from the latest turbine projects.

In the oxy-combustion process the pure oxygen is produced from air by a cryogenic Air Separation Unit (ASU) which is mature technology supplied by numerous international companies worldwide. In the early part of the project ASU was modeled using Solvo™ power plant simulator's ASU-component. Component consist compressor stages, coolers, molecular sieve and a distillation column. By implementing ASU component to the model it was possible to approximate the electricity and cooling consumptions of this unit with different loads of the oxy-fuel plant. The purity of the oxygen is chosen to be at 95 vol-%.

The greatest uncertainty in overall cost and performance of an oxy-combustion power plant lies in the CPU and storage costs. The transportation and storage technology and costs are estimated following the methodology of Kujanpää et al [6].

3. Summary of studied cases and default values for economic analysis

Different cases with different shares of biomass and application of CCS are investigated in order to analyze the impact of different GHG mitigation solutions for the plant, see Table 1. These case specific input values are results of detailed plant modelling with different technologies. The focus has been in CHP (without condensing tail in turbine) but two power production (condensing) cases based on the same boiler properties were added for comparison of CHP and power production solely (cases 1b and 4b).

Table 1. Summary of considered cases.

	Reference case	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 1b**	**Case 4b**
Plant type	CHP	CHP	CHP, oxyfuel	CHP, oxyfuel	CHP, oxyfuel	Power	Power, oxyfuel
Fuel input [MW], based on LHV	420	430	430	440	420	430	420
Annual fuel use [GWh/a]	3106	3093	3075	3083	3087	2375	3185
Fuel mix [% of energy]	43% bio + 57% coal	90% bio + 10% coal	43% bio + 57% coal	100% bio	100% coal	90% bio + 10% coal	100% coal
Heat production [GWh/a]	2076	2303	2353	2600	2087		
Electricity production [GWh/a, net]	907	859	544	479	610	880	880
Investment % compared to reference case	100	105	180	185	175	105	175

Default values for economic evaluations are presented in Table 2. However, as the power plant investments are made for decades and the future is uncertain the focus of this paper is in sensitivity analysis rather than in these default values.

Table 2. Default values for economic analysis.

Weighted average cost of capital (WACC)	5 %	
Economic timeframe	25	years
Coal price	10	€/MWh
Biomass price	20	€/MWh
CO_2 emission factor for coal	92.4	tCO_2/TJ(fuel)
Capture rate	99 %	
CO_2 allowance price	20	€/t CO_2
CO_2 transport&storage cost	20	€/t CO_2
Additional O&M in CCS cases	4	€/t CO_2 captured
Electricity market price	50	€/MWh
Economic value for heat	40	€/MWh

The cases with significant share of biomass combined with CCS results in “negative” CO_2 emissions, (carbon sink) i.e. removal of CO_2 from atmosphere from life cycle basis. Regulation regarding EU ETS [7] is not ready yet to accept negative emissions, even if from the climate change point of view captured and stored bioCO_2 is as valuable as stored fossil CO_2 in comparison to the situation that the same amount of fuel is combusted without capture. The discussion regarding carbon neutrality of biomass (carbon debt etc.) is important, but extremely complicated story regarding fuel in general, not value added by CCS. Therefore there should not be a difference between acceptable CO_2 emission reductions in the plant whether the captured CO_2 is fossil or biogenic. Contrary to the existing regulation, we have used the same price for CO_2 allowances also for negative emissions (otherwise it is obvious that bioCCS would not be feasible).

Other O&M costs (fixed and variable) for the plant were estimated based on Eq. 1 and Eq. 2. The equations are obtained by fitting to data, which has been collected from power plants utilizing significant proportions of biomass in fluidised bed boilers. Additional costs in the case of biomass co-firing include for example additional chemical & maintenance costs in comparison to reference case boiler operation. In addition, in this study the requirements for large biomass shares are taken into account also in the additional investment in comparison to the reference plant (which already was designed for significant share of biomass).

$$\textit{Variable O\&M [€/MWh, fuel]} = 0.00024 * P_{bio}\text{^}2 - 0.0076 * P_{bio} + 1.08 \qquad \text{Eq. 1}$$

$$\textit{Fixed O\&M [€/kW, fuel]} = 0.0002 * P_{bio}\text{^}2 - 0.0014 * P_{bio} + 14.037 \qquad \text{Eq. 2}$$

Where P_{bio} is the proportion of biomass [% of fuel energy, based on LHV].

In this study we assumed that for condensing cases the annual electricity production stays equal. Common parameters were chosen to enable more transparent and easier comparison between cases. In reality, utilisation rates for all of the studied cases would be different due to for example different variable costs of electricity production. More detailed determination of utilization rates would have required hour-by-hour analysis taking into account for example electricity price variation in the future, which would include significant uncertainty in any case. The selected annual electricity production for power plants is calculated based on assumed peak load utilization rate of 5500 h/a for case 1b.

4. Results

The major costs associated to CCS are caused by the equipment investment, loss of electricity production due to energy penalty and transportation and storage of CO2. The costs associated to biomass combustion with high shares are mainly caused by higher prices of biomass fuel in comparison to coal and lower power-to-heat ratio. Large biomass share has an increasing impact also on plant investment and O&M costs. On the other hand, significant savings are achieved in terms of CO_2 allowances, if predicted high prices will come true. In CHP environment also the changes in heat generation between different plant options and cost of additional/ substitutive heat energy sources in the whole district heating systems need to be taken into account. The focus in this paper has been in sensitivity analysis (Figures 3 - 5). However, in Figure 2 the breakdown of additional costs, incomes, savings and profits in comparison to reference case are presented for all considered cases.

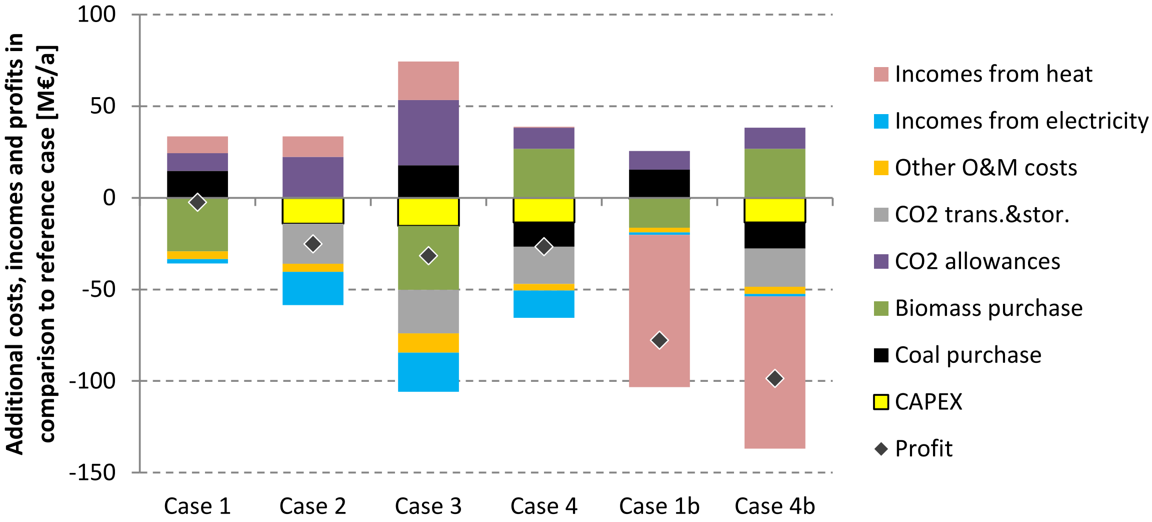

Figure 2. The breakdown of additional annual costs, incomes, savings and profits in different cases in comparison to reference case by default values.

According to Figure 2, none of the considered cases is feasible in comparison to reference case. However, relatively low value for average price of CO_2 allowances was used as default (20 €/t). ”Negative” CO_2 emissions are reached in the cases 2 and 3 (-505 kt/a and -1.2 Mt/a, respectively). In Figure 2 all CO_2 reductions are visible as incomes as Figure presents the difference in comparison to reference case. In the following figures, the profitability of studied cases is compared in different market situations and with sensitivities for selected parameters.

It is evident that higher CO_2 prices and other targets to increase renewable energy, as well as other competition on sustainable biomass resources will increase the price of biomass in long term. As the carbon prices have been relatively low in Europe, the penetration of CO_2 prices on biomass pricing has not been verified yet. The penetration probably depends also on location. In Finland, biomass is relatively cheap due to vast natural resources and large forest industry offering by-products for combustion from forest management to bark from debarking plants. However, this is not the case all around the world where the resources of sustainable biomass are more limited. In Figure 3, the most profitable options of three considered CHP cases (reference, case 1 and case 4) are presented as a function of average prices for biomass and CO_2 emission allowances.

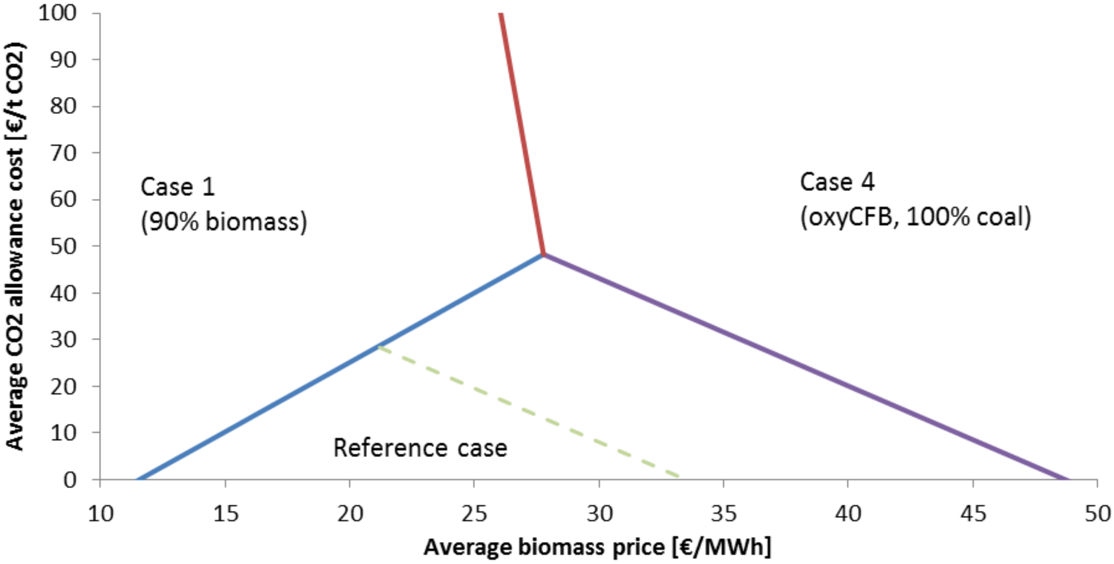

Figure 3. The comparison of profitability between reference case and two options for significant reductions in CO_2 emissions. The dashed green line indicates break-even prices (BeP's) for Case 4 if only capture costs are included (i.e. captured CO_2 is for example utilised, or transport and storage are significantly cheaper elsewhere).

According to Figure 3, the reference case and increased biomass proportion are the most profitable options with current price levels for biomass in Finland. However, already at price about 28 €/MWh for biomass, oxyfuel becomes the most profitable of compared options, if CO_2 price is high. With lower CO_2 costs, the reference case is the most feasible of the considered options, even with higher prices for biomass.

For the studied CHP cases not presented in Figure 3, the BeP's are presented in Figure 4 as a function of biomass price. As Figure 4 shows, with current level of biomass prices in Finland, also the cases resulting "negative" CO_2 emissions (cases 2 and 3) would be feasible with realistic future prices of CO_2 allowances (about 35 to 45 €/t). Condensing cases are not competitive against the reference case utilizing CHP.

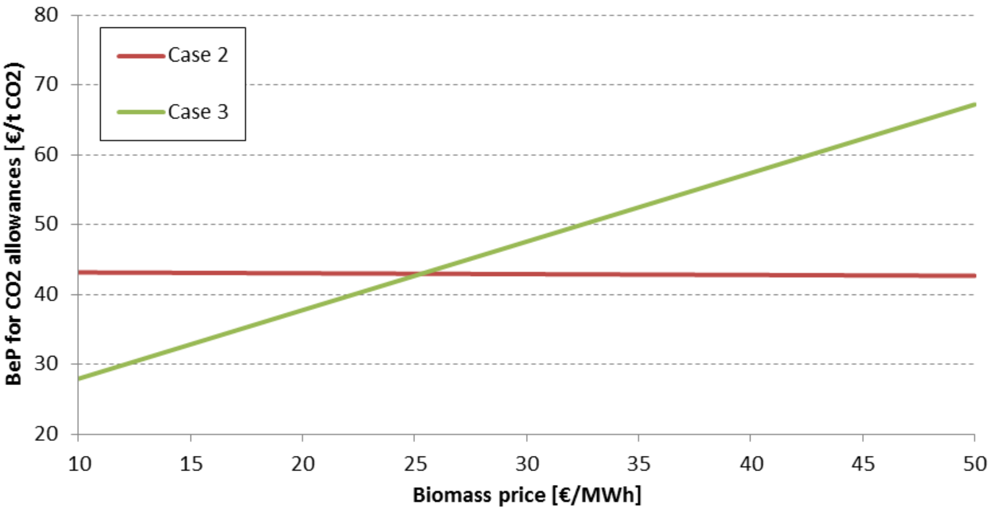

Figure 4. The break-even prices for CO_2 allowances to turn studied cases resulting "negative" CO_2 emissions (cases 2 and 3) feasible over the reference case.

In general, CHP is more feasible than power production solely, if there is heat demand. In Finland, long and cold winters during history have helped to create extensive infrastructure for CHP (heating network i.e. pipelines for hot water in all cities) and therefore investments on this network are not taken into account in the values presented in for example Table 1. Obviously there is a certain need for heat around the world (domestic water use etc.) but extensive district heating network is not always available. If the network is there, the required value of heat to turn CHP more feasible than condensing case is presented in Figure 5 as a function of electricity selling price. In the figure, feasibility of condensing production cases (1b and 4b) are compared with CHP cases (1 and 4, respectively). The break-even prices increase as of function of electricity price because electricity production efficiency decreases due to CHP. Relatively low prices (e.g. in comparison to district heat prices for consumers, or prices of alternative heat sources) are enough to make CHP more feasible, even with high electricity prices. It should be noted, that this figure is sensitive for assumed peak load utilization rates of condensing power plants as actually utilisation rates would not be constant with such a large variation in electricity prices presented in horizontal axis. This also makes the figure unrealistic in the lower end of electricity prices, as for example oxyfuel plant would have high utilisation rate despite of continuous defeat in condensing case. Comparison of oxyfuel cases seems to be more sensitive for electricity price as there is larger difference between annual electricity productions of condensing case and CHP case than between air firing cases. This is due to approach used for defining the annual productions (see section 3).

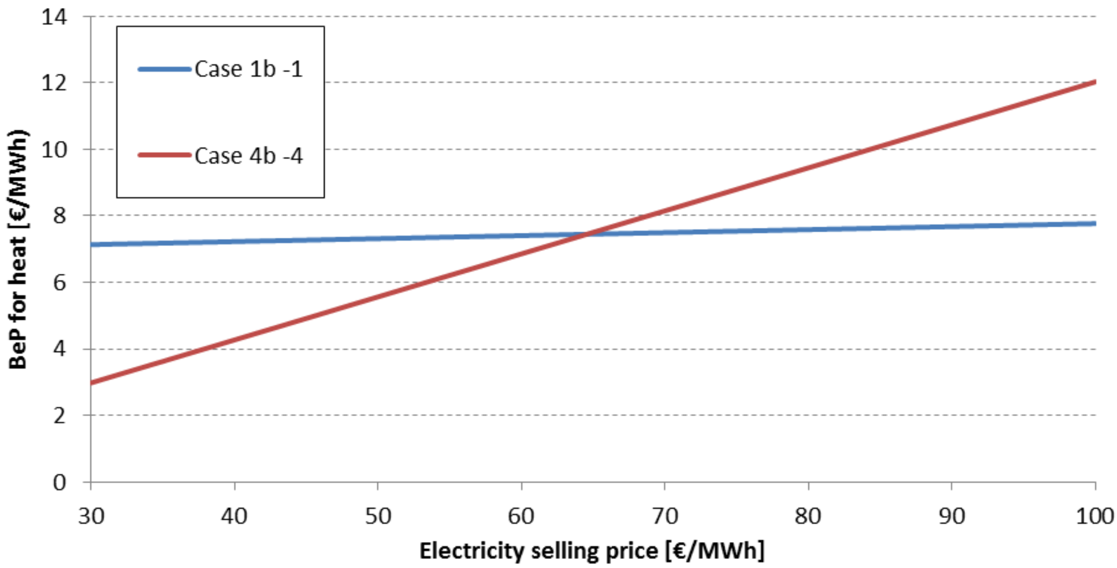

Figure 5. Required value (or break-even price, BeP) for heat to turn CHP cases (1 and 4) more feasible than condensing cases (1b and 4b, respectively) as a function of electricity selling price.

5. Conclusion and discussion

In this paper, the feasibility of co-firing of large shares of biomass was compared with feasibility of similar CO_2 emission reduction levels by utilizing oxy-CFB with CCS. In addition, two cases resulting "negative" CO_2 emissions were studied. The paper highlights the uncertainties and sensitivities for biomass prices, CO_2 prices as well as prices for electricity and heat (in the case of CHP). In addition, there are several other sources of uncertainty, which could not be presented in this paper. For example utilization rates of the plants are sensitive for electricity prices, fuel prices, etc., but especially dependent on heat demand in the case of CHP. In addition, if condensing tails are utilized, optimization of utilization rates of CHP plants becomes more complex and depends also on other heating plants in the network, their fuels, flexibility, potential heat storages, etc. In this paper, condensing tail was not included in CHP plant. Depending on assumed electricity prices, and hourly variation of it, condensing tails may become feasible especially in the case of oxy-CFB, as it would compensate decreased power-to-heat-ratio.

In this paper a real CHP plant project in Finland was used as a basis for the studies. Therefore also EU ETS was used as incentive mechanism for emission reductions. In some regions, also CO_2 emission performance standards (EPS) are presented meaning the limit for specific CO_2 emissions per produced electricity. Typical presented levels are around 400-550 g/kWh. In this study, most of the considered cases would easily reach these levels even if all emissions are allocated for electricity. If allocation of CO_2 for several products is accepted, CHP would be effective in reaching presented EPS. However, in general CHP is more feasible than condensing production if heat can be delivered to customers with reasonable price. In this study, some process steam was also delivered to customers and the value was included to heat price. If steam would not have been delivered, efficiency of electricity production would increase. Thus electricity production efficiencies are higher in some CHP plants in Finland. However, supply of process steam from same CHP plant than district heat is also a widespread solution in Finland.

Due to the more ambitious climate policy in future, other targets for renewable energy and other competition on biomass (existing forest industry, targets for liquid biofuels, etc.), biomass price may increase significantly, at least in the areas where limited amount of sustainable biomass is available. Increasing biomass prices make applying of coal fired CCS more competitive against biomass co-firing with large shares when same magnitude of emission reductions are sought. According to results of this study, oxy-CFB may become competitive against large biomass shares with quite realistic future prices for biomass and CO_2. However, in reality there are also taxes for fossil fuels and other subsidies for renewables which were not taken into account in this study. Therefore emission reductions with coal and CCS are at the moment less feasible than presented in the figures of this study, at least in Finland. The approach to exclude taxes and other incentives than EU ETS was chosen to make the paper more transparent and easier to adapt also for other regions. In addition to other incentives and taxes, feasibility of CCS in comparison to co-firing is also hindered by the risk related to larger investment and less mature technology (in power plant scale and related to whole CCS chain). On the other hand, investment on large CO_2 emission reductions by large proportion of biomass includes risks as well due to potentially increasing competition of sustainable biomass and political discussion about carbon neutrality of biomass. However, it seems that the major factor effecting the technology decision is plant location in relation to availability of biomass, coal and CO_2 transportation&storage options, as well as heat demand (possibility to utilize CHP) in addition to political atmosphere and acceptability of technologies.

From the climate change point of view, captured and stored bioCO_2 is as valuable as stored fossil CO_2 in comparison to the situation that the same amount of fuel is combusted without capture. Therefore there should not be a difference between acceptable CO_2 emission reductions in the plant whether the captured CO_2 is fossil or biogenic. This is not dependent on the discussion regarding carbon neutrality of biomass (carbon debt etc.), which is extremely complicated story, including different types of biomass, waste streams, reference scenarios and potential impacts on forestry and forest industries and the production resulting already now significant carbon stocks and thus "negative" CO_2 emissions.

Acknowledgements

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